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Achieving Reliable Information from Extensive Sensor Cluster Networks on Ships

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CONTENTS

1. INTRODUCTION	1
2. IN-SERVICE CALIBRATION AND TEST OF MEMS SENSORS	3
2.1 Active Self-Calibration	3
2.2 Active Self-Test	5
2.3 External Stimulus	6
3. REDUNDANCY FOR RELIABLE INFORMATION	6
4. CERTIFYING AND MONITORING SENSOR STABILITY	7
5. SOME PRACTICAL ISSUES	8
6. CONCLUSIONS AND RECOMMENDATIONS	12
ACKNOWLEDGMENTS	16
APPENDIX I—Selected Notes on Discussions with MEMS Researchers and Manufacturers . . .	17
APPENDIX II—General Considerations for MEMS Sensor Systems	18
APPENDIX III—Estimates for Sensor Failure and Maintenance	19

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ACHIEVING RELIABLE INFORMATION FROM EXTENSIVE SENSOR CLUSTER NETWORKS ON SHIPS

Abstract

This report is the result of a study that seeks to provide guidelines for obtaining reliable information from a sensor network that frequently or continuously monitors the interior status of a ship. It complements other reports in preparation from NRL. Approaches include built-in test (BIT) and built-in-calibration (BIC) but they have drawbacks. The primary finding and recommendation of this study is that redundancy is feasible and is the most cost effective route for achieving reliable sensor data.

1. Introduction

The original goal of this project was to develop and demonstrate a systems approach to calibration of the proposed network of MEMS sensors that will monitor a ship's condition, and, by so doing, enable a significant reduction in the size of the ship's crew.

In order to produce a plan for calibration of the sensors on the SC-21, information presently available about the types of sensors to be used and their characteristics is being assembled by NWAD. Once the up-to-date overall picture of the sensor arrays was in hand, then a plan for sensor calibration could be formulated.

In formulating this program, it was thought that the calibration plan would break down the following way, depending on the findings of the initial study:

- a.) determine if a sensor is already accurate and contains sufficient built-in calibration that can be interrogated remotely by computer and, therefore, is approved for use;
- b.) encourage manufacturers of particular MEMS sensors to make design changes (mechanical or electrical in nature) in order to ensure that the MEMS device will have built in calibration;
- c.) if (a.) and (b.) are not possible, recommend inexpensive means to calibrate the sensor which may entail manufacture of a new MEMS device for calibration purposes, or modification of ship design to accommodate sensor calibration.

This study would help ensure that the latest thinking regarding the SC-21 design and the most up-to-date MEMS technology are incorporated into the program.

As NRL began to execute this plan, it quickly became apparent that the entire notion of calibration of MEMS devices was mismatched with the advantages MEMS devices. That is, the key issue is really sensor "reliability" and not "calibration" per se. In fact, calibration is not the only way to insure reliability, and it may not even be the optimum method. The reasons for this are detailed in what follows. Part of the motivation for this change in thinking came directly from contacts with MEMS manufacturers who do not presently have built-in-calibration and are not anticipating implementing it in the near future. The same fundamental factors should apply to all programs that intend to install large numbers of sensors on ships including; reduced manning ships by virtual presence (RSVP), condition-based maintenance (CBM), integrated condition assessment system (ICAS), the damage control-automation for reduced maintenance (DC-ARM) programs, among others.

In order to understand the logic in recommending this change in emphasis of the BIC-MEMS program, we first present an general review the various ways to perform in-service calibration of MEMS sensor packages.

2. In-Service Calibration and Test of MEMS Sensors

In principle there is only one NIST-traceable standard that can be transferred to a remote sensor via a network, and that standard is "time" (or time interval). All the rest (acceleration, force, pressure, voltage, current, resistance, etc.) require that a known input (a traceable standard) be present in order to perform a calibration (test measurements with known inputs). This limitation is not just a question of engineering, it is a fundamental physical limitation. In most cases providing a traceable standard at each sensor is unreasonable, impractical, or impossible.

The next best solution to traceable calibration is to provide a stimulant to a standard. For example, a sensor could use internal or external circuits and/or actuators to supply highly reproducible forces, voltages, etc. to a sense element, and then measure changes in the health of the sensor by examining the output. This is really a self-test function and not a true calibration. However, with this self-test method, it is not possible to distinguish between sensor degradation and degradation of the components used to test it. In the discussion that follows, we will use the term calibration in the weakest sense of the word in order to include the widest possible array of calibration methods in our discussion.

2.1. Active Self-Calibration

2.1.1. Mechanical Actuators

The designs of sensors based on capacitive, piezoresistive, or piezoelectric sensing of a moving part are readily adapted to built-in calibration and recalibration of the displacement transducer. These are usually a surface or bulk micromachined free-standing membranes, cantilevered beams, or spring systems and are used in many pressure, vibration, acceleration sensors. Their design may be modified to provide a range of electrostatic forces to actuate these displacement transducers and then to use an associated computer to generate a calibration table from the measured responses. For all three sensing mechanisms, extra electrodes must be added to the device and additional engineering is required.

There is a difference between calibration check and recalibration. In the former, a control circuit (usually the onboard ASIC) compares the signal output level for each applied voltage level to a stored set of numbers. If the comparison is within a specified limit, then the device is in calibration. If it is not, then the options are to replace the sensor, or, to store a new set of numbers and thereby affect a recalibration. However, why are the numbers different? Is it because the

applied standard voltage has changed, or is it because of a change in the physical properties of the piezoresistive (piezoelectric, capacitive) read-out device, or is it because of a change in the stiffness, or the bias of the membrane (cantilever, spring), or is it some other failure mode? Storing a new set of numbers recalibrates the sensor but to what value? The only true way to recalibrate the device is to actually apply a known pressure, acceleration, etc., that is to redo the initial calibration.

2.1.2. Electrical Sensors

For sensors that operate by measuring changes in current or voltage in a resistor or diode, as in many temperature and humidity sensors and some pressure sensors, electrical circuits can be employed in some cases that test the operation of the sensor. It is also recognized, however, that certain temperature and humidity sensors are inherently difficult to calibrate due to the fact that a precise voltage reference cannot be made to mimic temperature or humidity. The best that can be hoped for is a self-test that could employ, for example, a heater to affect a change in the temperature or humidity, which is recognized by the sensor. This indicates that the sensor is working, but does not constitute a calibration.

It is anticipated that a device is more likely to fall out of calibration than it is to fail completely. However, technical barriers exist for the calibration of these sensors. Development of appropriate calibration methods will require additional time, since it is not clear how to maintain the calibration of the on-board test circuitry and hardware (which require additional electrodes). It is probable that even in self calibration-capable MEMS, certain electrical circuits used will still rely on uncalibrated, but known-to-be-reliable electronic circuits and devices (such as constant voltage sources). At this time, we do not know of any commercially available MEMS sensors that allow a full calibration check or a recalibration, but it is an active area of research in the MEMS community (The Analog Devices ADXL accelerometer's self-test is a one point calibration check). Although this is clearly a very desirable feature, it is not clear how many sensor types are being researched for inclusion of self-calibration, when such devices will be available, or what the cost of such devices will be. Pressure and acceleration sensors are most amenable to potential self-calibration schemes.

In order to implement 1.1 or 1.2, a high stability voltage reference is required.

2.1.3 Onboard Voltage and Current Standard

Small, low-power, band-gap voltage references are commercially available for less than a dollar. If such sources have adequate reliability, stability, and precision, then sensor circuitry and actuators can be calibrated with such voltage references. Similarly, commercial constant current sources are available with a wide variety of specifications and in a number of different configurations. Such devices are necessary for the operation of diode-based thermometers.

2.1.4 Transfer of Calibrated Voltage to Device

An alternative voltage reference was suggested by Harold Glick. A frequency-to-voltage converter can be used to generate a standard voltage from a calibrated frequency sent to a sensor. That voltage could then serve as a reference to calibrate a device. Clearly, this method requires the reliability qualification of the frequency-to-voltage conversion device.

2.1.5 Reliability of Electronic Circuits

The large amount of data on reliability of CMOS circuits, and the vast experience of electrical engineers with CMOS circuits, support the fact that circuit designers are very comfortable with the reliability and consistency of various electronic circuits. Such designers may predict that electronic portions of self calibration schemes do not need to be calibrated themselves, once they are designed and tested. Therefore, solutions 2.1.3 or 2.1.4 would not be necessary if the reliability of critical CMOS ASIC circuits that control MEMS devices can be established.

2.2 Active Self-Test

2.2.1 A sensor with active self-test has the ability to determine if the device is functioning correctly, but it will not tell you if the calibration is wrong. At best it indicates that the sensor should be changed. The exact mechanism used will depend on the specific sensing mechanism. Prime examples are electrostatic deflection of membrane, cantilever or other spring-based pressure and acceleration sensors. A voltage applied to the extra electrodes produces a voltage from the readout, or provides an impulse to the device that makes the membrane, cantilever or spring "ring" at its natural frequency. Other examples include on-chip heating elements for temperature, humidity, and chemiresistor chemical sensors. Strictly speaking, these devices do not allow calibration, but they provide an indication that the device is in a "normal" operating range and that the signal coming from the device is "likely" to be correct. See below for more discussion of what "likely" means. Such yes/no self-test features should be incorporated into the initial design.

2.3. External Stimulus

2.3.1. Natural

An example of this is barometric pressure. Calibration is performed at the times of high and low pressure that naturally occur due to changing weather patterns. Readings from the sensors are compared to a single, precision pressure gauge.

2.3.2. Artificial

2.3.2.1. This option would require a roving worker to walk around the ship with a 'test instrument' that is known to be accurate, and manually check each sensor on some periodic schedule. This instrument would be pre-programmed to do all the necessary test/calibration tasks, and would be plugged in to each sensor (or sensor set) to verify the proper operation of each device. This option is costly, labor intensive and time-consuming, and it also fails to detect malfunctions between testing times. It is the primary method used for today's shipboard sensors.

2.3.2.2. Stimulation is accomplished by placing a second device near the sensor that is centrally controlled and can be remotely ordered to conduct the stimulus test. This is similar to 1, but the test hardware is independent of the MEMS sensor package, and must itself be calibrated. It too is a complicated, costly solution.

3. Redundancy for Reliable Information

3.1 Homogeneous Redundancy (Same Sensing Mechanism)

Confidence in Calibration can be assured indirectly by using several identical sensors to measure the same quantity. The signals from each of the sensors are inter-compared, and a decision protocol determines the most probable value of the quantity and the confidence limits for that value. A sensor unit can consist of individual sensors packaged together and controlled by an ASIC, or manufactured together at the chip level and controlled by an ASIC. A sensor array is replaced when the confidence is less than satisfactory.

3.2 Heterogeneous Redundancy (Different Sensing Mechanisms)

This is a more robust form of redundancy, similar to 3.1 except that there are two or more sets of multiple sensors, and each set operates on a different physical principle in order to measure the quantity of interest. Examples are given in Table 1 where for one mechanism, there is at least two identical sensors that are compared, and for two mechanisms, there is at least one of each type of sensor that are compared.

Table 1 - Some types of redundant sensor membrane, cantilever or spring arrays.

Sense mechanism	Redundancy		
	Option I	Option II	Option III
Piezoresistive	X	X	
Capacitive	X		X
Piezoelectric		X	X

Heterogeneous redundancy avoids a potential problem with homogeneous redundancy. That is, it is possible that all of the identical sensors of a given set will degrade uniformly (e.g., age at the same rate) and, therefore, all give the same but erroneous reading. This would not be noticed by an algorithm that relied in comparison between sensors of a given sensor set.

If the performance of a sensor decreases with the time that is under power in both 3.1 and 3.2, then a practical use of the sensor arrays could include the use of one unit of an array as the primary sensor, and the others used to "occasionally" confirm the correct operation of the primary sensor. This method has the advantage of keeping the secondary device off-line most of the time, and thus, minimizing the chance of the secondary sensors failing. Redesigning a standard sensor with 2 to 6 identical sensors on a chip, instead of cutting individual sensors from the die, is a straightforward change to the manufacturing process.

4. Certifying and Monitoring Sensor Stability

Sensors from manufacturers must be checked to ensure that they meet the specifications when initially purchased, and after sitting on the shelf for many years. This is especially important if method 3 or the method described in the next paragraph are used for calibration assurance. In addition to normal specifications for devices, such as dynamic range, calibration precision, sensitivity, input power, frequency response, temperature stability, etc., it is important to include response time (how long does it take the sensor to notice a stimulus).

While it is not a true solution to the problem of obtaining reliable information from sensors, it is worth pointing out that many failures can be recognized simply by comparing current data to previous data a sensor has generated. If the output suddenly jumps off scale, or starts behaving erratically when the data history has normally been a smooth and steady response, this indicates something is wrong, and that the sensor should be changed. Although the method is simple, it may be appropriate in some cases where the sensor output is not life threatening. It is also a very low-cost solution. The basis for this method is the expected stability of MEMS sensors. In order to implement this approach, the stability of each sensor used would have to be determined. This is in itself challenging because life tests take time and accelerated testing is usually questionable.

5. Some Practical Issues

Reliability, lifetime, and calibration go hand-in-hand. For a shipboard system with upwards of 200,000 sensors to work effectively, it must have long life, be simple to maintain and easy to repair when trouble is noted, and the information it provides must be believable. The sensors, by definition, must be robust, reliable, and within the calibration specified while in use. A practical way to handle the calibration is to discard a sensor whenever parameters monitored by the system undergo a change. Highly calibration stable sensors could be handled in this way. What is required is solid engineering data on the long-term behavior of the sensor, and good quality control and repeatability from the manufacturer.

Since the promise of MEMS is inexpensive, reliable sensors, and since many devices or circuits can be packaged together on the chip with little cost penalty, redundancy may be affordable. Therefore, redundancy could be used extensively to enhance not only calibration accuracy, but sensor array lifetime as well.

In solving the calibration problems, one should always search for the simplest and most practical solutions. The addition of sophistication to a MEMS device, however, may be a practical solution in some cases. The additional hardware and software only have to be designed and added once. The device may still be affordable due to batch processing.

The notion that all sensors must have calibration traceable back to NIST standards is an admirable goal. However, this exacting process may not be practical, achievable, or even necessary in order to carry out the mission. For example, it may suffice to calibrate against NIST standards before deployment, and thereafter look for a change in the operating parameters.

In arriving at a plan for the successful implementation of MEMS sensors on a ship, it is worthwhile to recall the advantages of MEMS sensors. A MEMS device consists of; 1) a sensor/actuator, 2) and integrated circuit. MEMS technology is mainly characterized by the items in the following table:

ADVANTAGES OF MEMS	
Main Properties	Miniaturization
	Arrays
	High Resolution
Main Benefits	New Applications
	Cost Effective at High Volume (not necessarily cheap!)
	Leading-Edge Performance
	Small Size and Low Power
	Multiple Sensors per Package

Nowhere in this list is the word "calibrated" specifically listed. All the listed items can be useful to the program. In discussions with MEMS experts, we find that devices with factory calibrated output over their operating range are relatively expensive versus those that are designed to give yes/no information. Here, factory calibrated means no ability to self-calibrate once it leaves the factory.

This type of information prompts two graphs that summarize the cost-benefit trade-off for calibrated MEMS. Tentative versions of the graphs are given below, based on discussions with several MEMS researchers and manufacturers.

Figure 1: Approximate Cost of Volume-Produced MEMS Devices

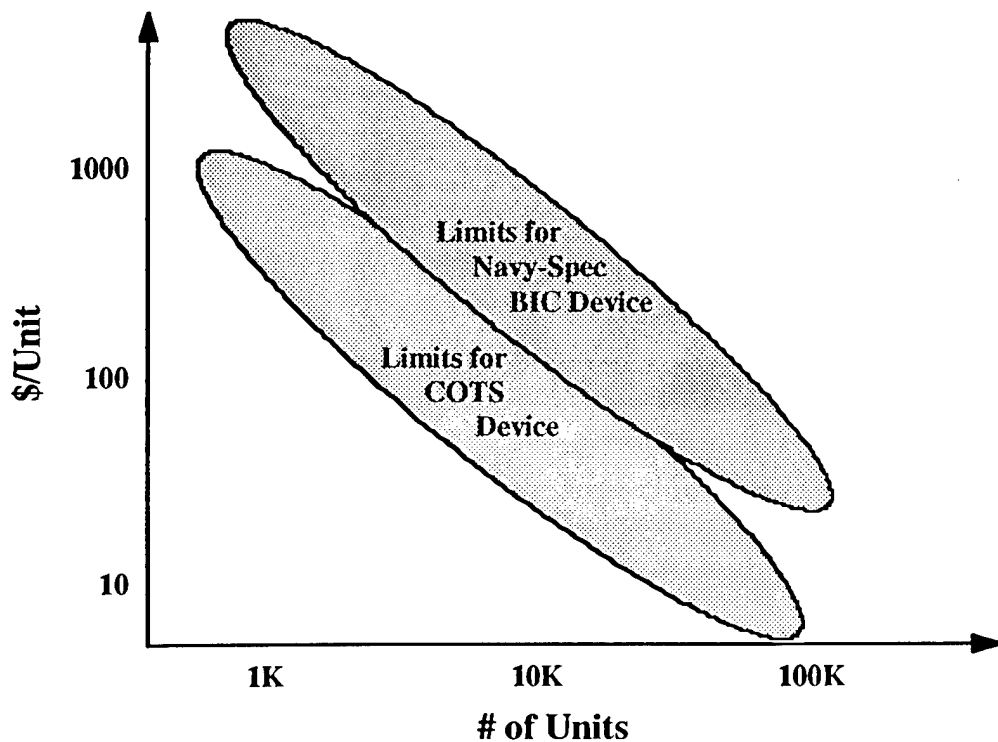


Figure 1 shows that for low cost, batch units of 100,000 or more must be built. It is likely that for a device with temperature compensated, initially calibrated output guaranteed by the manufacturer, the cost will be ~\$50 per sensor. This figure is tentative, but it conveys the spirit of the cost difference between simple COTS devices and more complicated MEMS solutions (~5x more expensive).

Figure 2. Device Confidence vs. Unit Cost

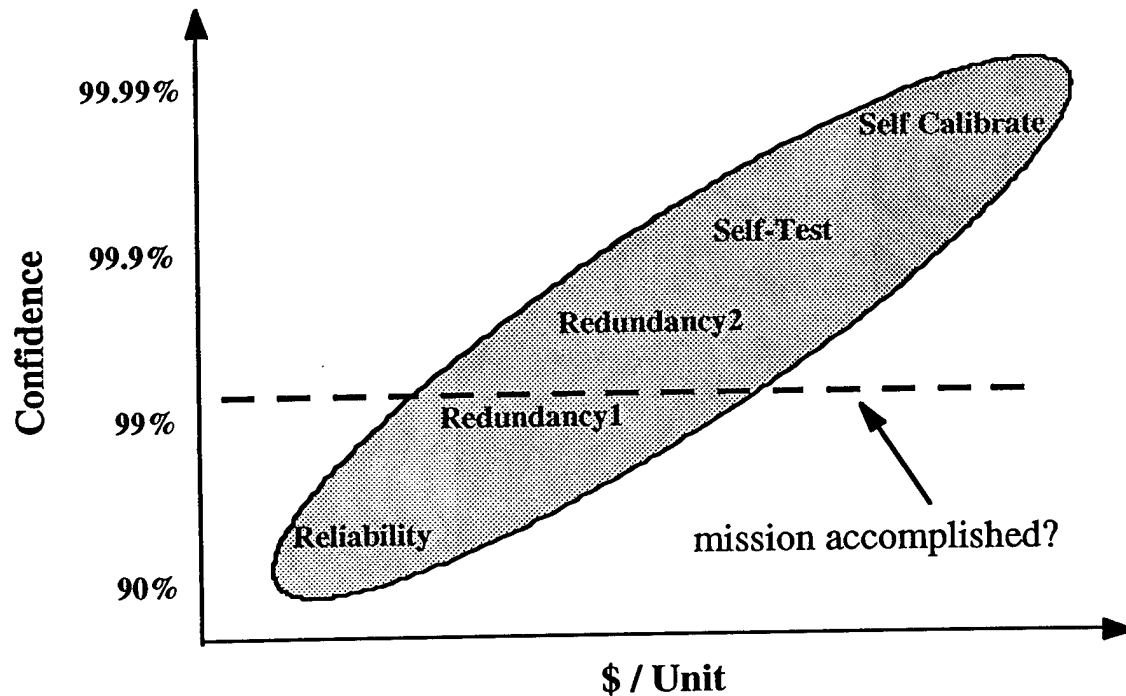


Figure 2 suggests a criterion for acceptability of the complication of the delivered MEMS devices versus cost. The Figure is schematic since it is not clear where to place the calibration assurance methods. Reliability refers to a single reliable sensor in a MEMS device which encompasses most of the present day sensor technology. Redundancy 1 means an array of similar sensors (homogeneous redundancy) that are inter compared. Redundancy 2 means two different types of redundant devices operating on two or more entirely different physical principles (heterogeneous redundancy) which are also intercompared. Self-Test means an uncalibrated indication from the device that is working within a wide specification window, and Self-Calibrate indicates that the device is capable of remote calibration. The simplest of these solutions that can solve the mission requirements will be the most cost effective.

6. Conclusions and Recommendations

In the following discussion we argue that if reliability is the key issue, then redundancy offers superior performance relative to periodic calibration.

Current practice is to hand carry a (traceable) standard to each instrument to be calibrated. This practice identifies an instrument that has already gone out of calibration. However, **calibration does nothing to insure that the instrument will not fail immediately after calibration.** Thus, calibration by itself does not insure that any later reading is valid. This practice serves mainly to validate old data and to identify those instruments that have failed or fallen out of calibration. Assuming we have a MEMS device that can be asked to calibrate itself, one still has to rely on methods 3 or 4 above to determine if the device is giving proper information in between calibrations.

The central question is then: Can we obtain a higher confidence in data with an alternate technique?

One alternate technique uses an array of instruments (redundancy) to determine the same measurand. **The high cost or redundancy may have been the reason that it has not been widely used.** However, with the low cost of MEMS arrays, redundancy is now cost effective. Moreover, it offers a higher degree of confidence in the final measured values than any other approach. This confidence can only come from having determined a quantity several times with different instruments. Redundant MEMS instruments can contain arrays of sensors and can be significantly less costly than a single large scale device.

Thus, in order to insure reliability of sensor information, we propose to replace each single sensor with several sensors, all of which perform the same function (although not necessarily in same way). We **calibrate these at the time of installation** and thereafter, we infer their continued state of calibration from the degree of agreement between their individual outputs. That is, we simply compare their responses (at the same time and for the same input). As long as all instruments are healthy, their outputs will agree to within some reasonable uncertainty. Then, we can continue to rely on their outputs. Aging errors of individual devices will be uncorrelated for devices based on different physical principles. Thus, aging phenomena can be readily identified and tracked.

If the output of a sensor or class of sensors begins to deviate from others in the array, then that fact can be transmitted to a central control point and

corrective steps can be taken. However, because there may be other sensors in the array that still agree with each other, a high level of confidence in the sensor data can be maintained even without taking any corrective steps. This is an important factor in a battle situation where repair of sensors is unavoidably delayed.

Reliability engineering provides a well established formalism for predicting the validity of the output of an array of sensors working in parallel. This can be quantified in terms of the performance factors of each sensor in an array. According to established theory, one only needs to specify the desired performance requirements (e.g., degree of agreement between array elements) to determine the corresponding requirements to place on the individual sensors within that array. Once this is established, one either publishes these requirements as a guide for COTS manufacturers, or one performs well-established testing techniques to evaluate existing COTS products to determine how many sensors will be required to meet the desired confidence limits. An authority on the reliability of electronic devices at NRL (Fred Danz) asserted that there are even ways to assess the confidence limits for devices that exhibit no failures during testing (which he claims is very common event with today's electronic devices). Details are available in a MIL Handbook on Reliability for Electronics.

This scenario seems to reduce the requirement for, or the utility of, self-test functions, unless it is necessary to evaluate performance over a wide range of inputs. In that case, the input to a sensor array must be simulated. Self test implemented in MEMS only approximates this solution.

There are significant technical difficulties and expense involved in transferring a standard (e.g., over a radio link) to a sensor. For example, additional circuitry must be designed and incorporated into sensor systems. Moreover, as stated above, the only standard that it is possible to transfer is time (or time increment). In any case, we must rely upon an assumed infallibility of additional devices on-board the sensor in order to convert the transferred time to some other quantity such a voltage. Since there is no justification for assuming such infallibility, the reliability of such a "pseudo calibration" is limited.

By the same token, one must treat the reliability of any on-board references with equal skepticism. Furthermore, even if one succeeded in affecting such a transfer of a standard, it is not clear that having done so provides any advantage over redundancy. For these reasons, we believe that redundancy is the preferred approach to achieving the maximum attainable reliability of sensor data, and that it can be accomplished at less cost per increment of improved confidence than any alternate techniques. Without reliability data, it is not

possible to predict whether method 4 will provide the required combination of lifetime and reliability of output, so method 3 is recommended.

After canvassing several developers and sellers in the MEMS community about how to handle the calibration/reliability question and melding their responses with our own research and ideas, we arrived at the following specific recommendations:

A. Insistence on calibration of a MEMS device is impractical in many cases

It may be too costly to produce a device that can be calibrated in the field.

Complications arise in assuring calibration of the on-board hardware and electronics required for calibration.

If a device calibration is run periodically, there is no assurance that it will not fall out of calibration before the next calibration check

There are, at present, no commercial sources of BIC-MEMS devices and it is not clear when, if ever, such devices will be available

Reliability and longevity of Built-in Calibration devices is unknown

B. Redundancy provides the highest confidence in sensor output.

Using arrays of devices, coupled with reliability engineering principles, not only provides instant built-in fault detection, but it also permits fully operational status to continue and repairs to be postponed. This capability is essential for extensive sensor networks. The miniature arrays take advantage of new capabilities offered by MEMS.

C. Any program that professes to provide solutions to the installation of 200,000 sensors on a ship should use sound reliability engineering principles and employ individuals with reliability engineering training.

D. Without MEMS sensors, the ship-building programs should be prepared to spend over \$100 per sensor (includes some onboard decision making, RF links, and power). If, however, commercial MEMS arrays become available and are used extensively with sound reliability engineering practice, then the cost might be under \$10 per sensor. If the reliability of single COTS sensors is sufficient to accomplish the mission (method 4 above), then the costs will be somewhat less.

E. Keep the design as simple as possible, and ask for as few changes as possible from an existing device from a manufacturer.

In general, this means that the micromechanical machined part contains very little electronics on it, and the electronic signal processing is handled by a ASIC on a mating part.

F. Actual MEMS devices for shipboard applications, in order to keep costs down, will entail minor modifications to devices already being built (nearly COTS).

For example, arrays of devices are already being manufactured on a chip, but are presently packaged as individual units. Redesign of the placement of devices to form small arrays is not too expensive, although additional costs will arise due to development of new packaging and new ASIC's. Developing an ASIC is relatively cheap since they can be modeled very quickly and ASIC technology is very agile and capable. It is much more expensive to develop new MEMS devices since the modeling is in its infancy. Trial and error, which are time consuming and costly, are still a large part of new device development.

G. The existing Navy infrastructure responsible for the reliability of sensors on Navy ships should be tasked with the responsibility to provide reliability engineers with performance data on candidate MEMS devices that can be compared to the output of reliability models. The reliability models will determine the lifetime required of the devices which are needed to enable the implementation of the extensive sensor system.

The responsibilities include:

- routine testing of as-received devices for compliance with specifications
- accelerated life-tests on batches of devices for reliability modeling
- accumulation of shelf-life data on sensors
- tracking replacement frequency of ship-board sensors to compare with models

H. Advanced research on CMOS devices for the space community has produced "low voltage electronics." We recommend a 6.2 research program to support testing this technology in a MEMS configuration, because of its potential impact on sensor lifetime and reliability issues. This technology is potentially very important because it could greatly extend the battery life of the MEMS device.

The new low voltage (and low power) technology, still in its infancy, uses gate voltages of one volt or less. The resulting circuits consume a factor of 10 to 500 less power than standard CMOS circuits. There appears to be no

technical barriers for implementing control ASICs for MEMS devices using this new technology. The primary systems issue is the increased chance of upset of the devices from electrical noise due to the lower operating voltages.

I. Low Power communications

Since RF communication could consume the largest of the power required for the sensor packages, a low power communications technique, such as modulated reflectance scheme for RF communication, should be considered. Such technologies could increase even further the very long battery life enabled by the new low voltage electronics technology.

Acknowledgments

We gratefully acknowledge very useful discussions with Dave Nagel and Michael Bell, and a thorough reading and editing by Dave Nagel.

• **Appendix I - Selected notes on discussions with MEMS researchers and manufacturers**

Andrew Mason, University of Michigan, August , 1998

Quotes: "Once an error has been detected there is very little you can do except replace the sensor (unless the device is capable of self-diagnosis). It may be possible to plug the malfunctioning device into a test chamber that would either tell you the device has failed completely or would recalibrate the device if it appears to be working fine, but this is not a simple task and could require a great deal of equipment including an environmental chamber ... to generate the proper test conditions."

"As I mentioned earlier, self-test, self-calibration, and other auto diagnostic features are still being worked on, but they appear to be a few years away from commercial markets. The best thing you can do now is buy a sensor that has a proven track record and be prepared to change-out devices that fail. In the future, as we add more and more electronics to sensors and sensor systems we may get to the point where a device can accomplish self repair. However, due to the nature of the sensor, it is quite difficult to accomplish in many cases (i.e. how do you remotely set the barometric pressure, humidity, temperature, etc. so that you can get proper test points for on-chip calibration?). Self repair is easier on a circuit where the data is all electronic, but with a sensor the data is 'physical' and hard to duplicate on-chip."

President of a European MEMS Manufacturing Company

Quotes: "Redundancy is the way to go. In fact, redundancy using two different sensing mechanism would be better."

"My company sells an accelerometer for \$7 that is a toggle - (that is,) it gives a signal above a set threshold. We sell a continuous output, guaranteed calibration accelerometer also. Mass produced it would cost about \$50. I do not know how reliable it is as there is no data. Of course, I believe it will be very good."

"We sell a MEMS device for use in Europe that reads the amount of hot water used and RF links the information to the utility company. It is very, very reliable, or the utility companies would not use it to generate income."

Appendix II - General Considerations for MEMS Sensor Systems

Although not addressed by this study, we urge the establishment of a standard sensor packaging, a standard bus structure, and a standard communications protocol for sensors. This would allow mix and match of components from different vendors and upgrading capabilities when new devices become available.

In order to reduce power requirement at each sensor we suggest a communication system based on modulated reflectance of RF energy. This is the same technology that is already in use in tagging schemes and at some highway toll booths. Each sensor is interrogated by a burst of addressed RF. The sensor responds by varying the impedance of its antenna and in this way varies the reflected energy. The information is digitally encoded in the time dependence of the reflected signal. Thus, the sensor does not use any energy used to generate RF, it simply modulates the incoming signal. The operation of this communication method is similar to using a variable reflectance corner cube reflector to extract information from a passive, covert listening device via a laser beam or microwave signal.

Appendix III contains simple computations that indicate that battery power is a marginal solution for providing sensor power. Battery technology is not yet advanced to ensure >5 year battery life, which we believe is minimally required from a maintenance and reliability point of view. The use of low-voltage-electronics and RF modulation may allow the use of battery power. The use of battery-powered devices would simplify the job of retrofitting of ships with sensor arrays by eliminating wiring harnesses. For new ship acquisition, we believe that bulkhead power should be provided for the sensor arrays. Communication could be accomplished by RF using the bulkhead power lines or a second companion set of lines.

The proposed network of RF links with sensors will likely meet heavy opposition from those concerned about the RF signatures of navy ships. One acceptable option may be to operate such a network at frequencies in an absorption band for water vapor. This would confine stray signals to the close proximity of the ship.

It may turn out that bulk micromachined and wafer-bonded crystalline silicon will be the MEMS manufacturing methods of choice. These devices have inherently greater temperature stability, and have fewer material interfaces than surface micromachined devices. Fewer materials and interfaces may translate into greater calibration stability and life-time. While this statement seems reasonable, there is presently no hard data to that confirm it.

Appendix III - Estimates for Sensor Failure and Maintenance.

A. Acceptable Failure Rate

Say there are 200,000 sensors on a ship.

Say failure rate for any reason is 1% per year.

Then 2000 sensors fail per year.

8760 hours per year/2000 failures = 4.4 hours between failures
or ~6 failures per day
or 2 failures per shift for a 3-shift 24 hour day.

This is probably the most failures one person could handle since it may take 10 min. to several hours to identify, locate, and change out a sensor, depending on its location and usage.

For reduced manning of ships, assigning more than one person to the sensors would defeat the purpose of having the sensors on board in the first place, since the 95 person crew is already assigned important functions to run the ship.

This estimate indicates that 1% per year is an upper limit to the acceptable failure rate, and that 0.1% would be much more acceptable for mission accomplishment. The calculations assume a uniform failure rate. More likely sensors will fail in bunches, overwhelming one assigned person.

This computation highlights the tremendous advantage of using redundant arrays of MEMS sensors, because such sensor arrays can continue to supply information with high confidence despite the failure of a sensor element. This significantly reduces the urgency of sensor maintenance.

B. Battery replacement

Say the average battery life is 3 years.

Say it takes an average of 10 minutes to walk to a compartment, locate a sensor and change the battery.

Therefore, in one 8 hour shift one person can change $480 \text{ min./shift} / 10 \text{ min./battery} = 48 \text{ batteries}$

To change 200,000 batteries in 3 months requires,

$$200,000 \text{ batteries} / 48 \text{ batteries/shift} = 4167 \text{ shifts}$$

$$4167 \text{ shifts} / 270 \text{ shifts/3 months} = 15 \text{ persons round the clock}$$

$$15 \text{ persons} \times 3 \text{ shifts} = 45 \text{ persons seven days per week}$$

45 persons is 50% of the ships crew working for 3 months to change the batteries.

From this calculation, it appears that a >5 year battery life is an appropriate target, so that this kind of manpower effort is no more than a roughly twice-per-decade event during refitting.